

# “CFD SUPPORT FOR JET NOISE REDUCTION CONCEPT DESIGN AND EVALUATION FOR F/A 18 E/F AIRCRAFT”

S.M. Dash, D.C. Kenzakowski, and C. Kannepalli

*Combustion Research and Flow Technology, Inc. (CRAFT Tech<sup>®</sup>)*

*174 N. Main St.*

*Dublin, PA 18917 USA*

CFD is being used to support the design and evaluation of varied passive concepts which have the potential to reduce jet noise on an F/A 18 E/F supersonic fighter aircraft. One aspect of the CFD support work entails basic concept evaluation which is being performed in collaboration with laboratory studies of Krothapalli at FSU and Seiner at NCPA/U.Miss. Concepts evaluated to date include microjets, chevrons and hybrid devices. CFD is supporting the optimization of these designs and evaluating how they will perform on a real engine. A new jet noise code is being evaluated which has the promise of quantifying the noise reduction obtainable. A major role is that of ascertaining the effect of plume/plume interactions as well as installation /aerodynamic effects which requires a very detailed, CPU intensive studies. Improvements to the CFD in the areas of RANS turbulence modeling are improving overall accuracy, while efficiency upgrades have been achieved via use of adaptive gridding on massively parallel architectures, as well as by use of new parabolized approximations.

## Introduction

CFD has been playing a very substantial role in supporting the design and evaluation of varied concepts for reducing supersonic jet noise, with a specific emphasis on jet reduction noise for the F/A 18 E/F aircraft. There are a number of specific roles that CFD is playing which include:

- (1) supporting small scale experimental studies by Krothapalli/FSU and Seiner/U.MISS-NCPA with regard to concept sizing, location, etc.;
- (2) scaling/modifying these concepts and evaluating how they would perform on the real engine in a strapdown (jet into still air) environment;
- (3) evaluating how these concepts would work in the flight environment of interest which includes investigating both plume/plume interactions and installation/aerodynamic interactive effects; and,
- (4) optimizing the performance of concepts found to work best with respect to both noise reduction and thrust loss minimization.

To date, our focus has been on item (1) above where we have performed simulations of

micro-jet effects [1,2] corresponding to experiments of Krothapalli and of chevrons [3-5] corresponding to experiments of Seiner. We have also done some preliminary work on item (2) via examining differences associated with the laboratory model and with the real engine. A major difference is in the internal mixing with the lab model using premixed fan/core streams and the real engine having complex slot injection to mix in bypass flow [6] which produces an exit plane profile that is only partially mixed. For the overexpanded operating conditions of interest, the concepts must be modified significantly to obtain the same level of noise reduction (after scaling of course) due to these internal mixing differences.

Some preliminary work has been done with regard to item (3). In particular, we have looked at both plume/plume interactions in a static surrounding environment, and compared single jet, dual jet, and full jet/aerodynamic solutions for a flight case. We have also supported system studies performed by Seiner for flight noise comparisons using ANOPP [7].

As part of this effort, we are making use of new technology stemming from our jet noise

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modeling work for NASA. This work entails fundamental turbulence modeling upgrades and exploratory work in interfacing with analogy based jet noise prediction codes. As a precursor to our design optimization work, we have developed fast parabolized methodology that permits obtaining the many solutions needed in an optimization study quite rapidly. A review of some highlights of our work over the past year follows.

### Jet Modeling Overview

Table 1 summarizes the principal features of the aeropropulsive  $k-\epsilon$  turbulence model [8] utilized for the studies performed. A present limitation for hot supersonic jets is the use of a constant turbulent Prandtl number. While we have incorporated scalar fluctuation equations [9] and a variable Prandtl number model [10] in our CFD codes, these have not been extended to account for compressibility effects which serve to diminish scalar fluctuation levels. Our work with more advanced explicit algebraic stress models (EASM) for jet noise applications [11, 12] is still at the research stage and the subject of current investigation in a NASA Glenn program.

Table 1. Aeropropulsive  $k-\epsilon$ -Model.

<ul style="list-style-type: none"> <li>Baseline high Re jet coefficients (Launder – 1972)</li> <li>Unified compressibility correction (cc) and compressible vortex stretching (cvs) correction</li> <li>Modified So-Zhang (sz) low Re and compressible wall function near wall models</li> </ul>
<b>Developmental</b>
<ul style="list-style-type: none"> <li>Weak shear correction</li> <li>Scalar Fluctuation Equations (<math>k_T/\epsilon_T</math>, <math>k_\alpha/\epsilon_\alpha</math>)</li> <li>Variable <math>Pr_t/Sc_t</math> Model</li> <li>Curvature/High Strain/Swirl Corrections</li> </ul>

Figure 1 shows a validation study of the aeropropulsive  $k-\epsilon$  model (termed corrected  $k-\epsilon$  model) as applied to  $M = 2.0$  hot jet of Seiner et al. [13]. Figures 1(a) and (b) show the comparison of the centerline streamwise velocity and temperature respectively for the jet compared with the experiment. One can see that the standard  $k-\epsilon$  model predicts a faster decay of the jet axis velocity while the corrected  $k-\epsilon$  model captures the correct decay. The slower decay is primarily due to the compressibility corrections (CC) decreasing the turbulence levels when compared to the standard

model. Compressible vortex-stretching (CVS) corrections have only a small affect for high speed jets. Note the major sensitivities in temperature decay to the value of turbulent Prandtl number utilized.

LES studies are in progress to provide scalar fluctuation data for hot jets [14]. Figure 2 shows results from LES shear-layers at convective Mach numbers of 0.27 and 1.3 (same velocity and temperature ratio). Reliable higher-order correlations involving temperature (Figure 2(b)) fluctuations (unavailable from experimental sources) can be extracted to determine the Prandtl number (Figure 2(c)) and Schmidt number variation.

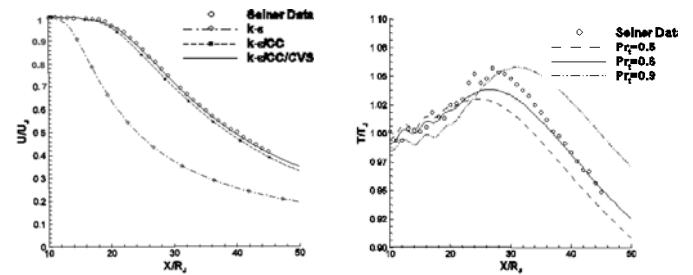


Fig. 1. Seiner Mach 2 Hot Jet.

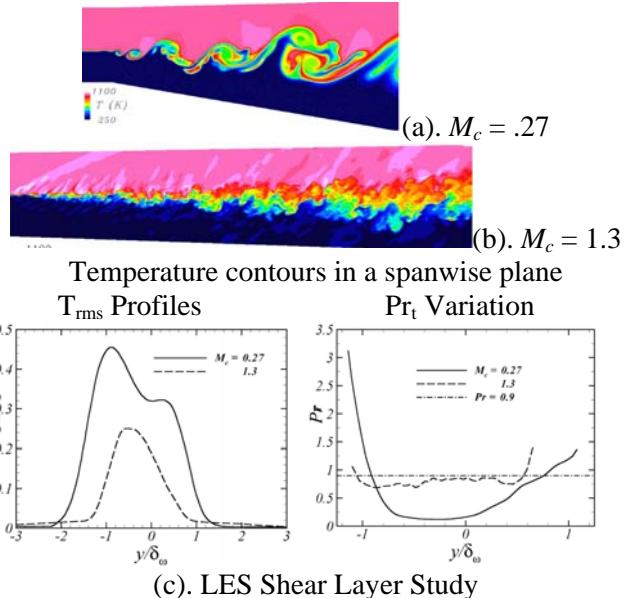
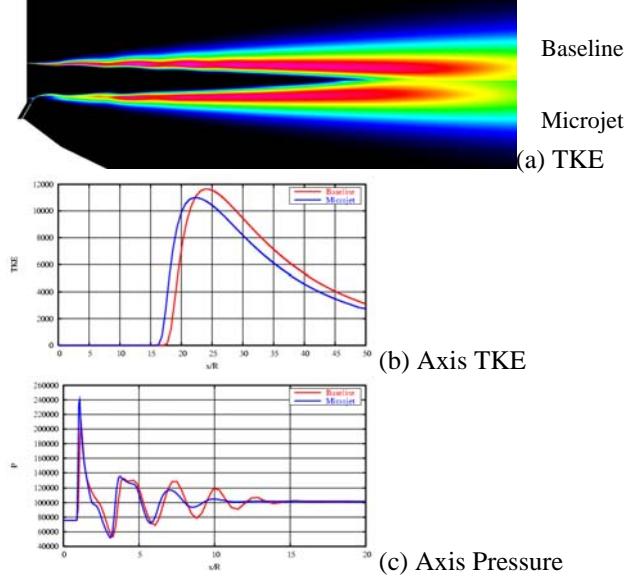


Fig. 2. Shear Layer Contours Exhibiting Effect of Convective Mach Number On Eddy Structure.

### Jet Laboratory Studies

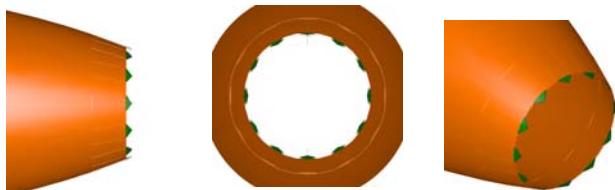
In support of FSU experimental studies of noise suppression with microjet injection, CRAFT Tech has performed a matrix of CFD simulations [1,2]. Earlier microjet injection was tested on underexpanded sonic nozzle. Currently, FSU is

investigating this concept for an overexpanded Mach 2 nozzle and Figure 3 shows some preliminary results exhibiting contours of TKE and axial variations of TKE and pressure with and without microjet.



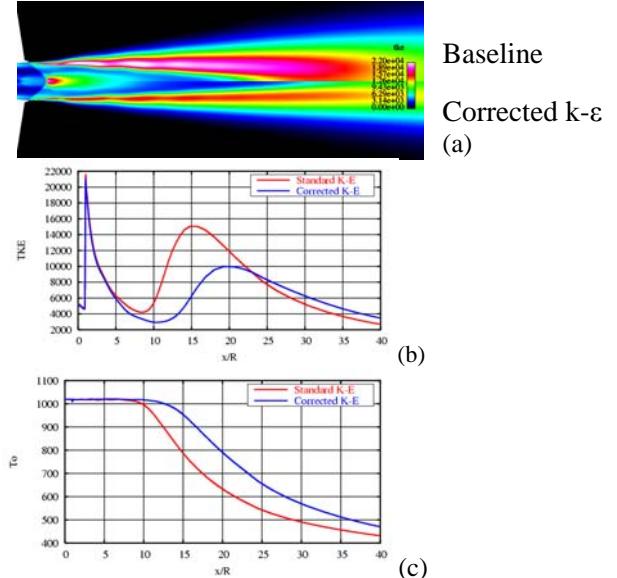
**Fig. 3.** FSU Overexpanded Nozzle.

We have analyzed the overexpanded NCPA nozzle fitted with three chevron designs (in both 6 and 12 azimuthal configuration, Figure 4) and compared them with results of the baseline nozzle.



**Fig. 4.** Arrangement of chevrons (green in color and 12 in number) at the nozzle exit.

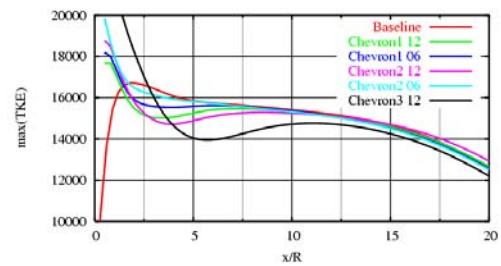
Insight into jet noise can be obtained from the jet CFD solutions. Figure 5 shows jet and TKE contours for the baseline case using the baseline and corrected k- $\epsilon$  models indicating that model selection will have a major impact on jet noise. With regard to effects of Chevrons, chevron 1 was small and inclined at  $45^\circ$  while chevron 2 was slightly larger and inclined at  $60^\circ$ . Chevron 3 was larger than 1 and 2 [4,5]. For chevron 1 and chevron 2 in both configurations of 6 or 12 chevrons around the nozzle exit, there are only small differences in the solution. Differences in the number of chevrons had a minimal effect on the flow structure.



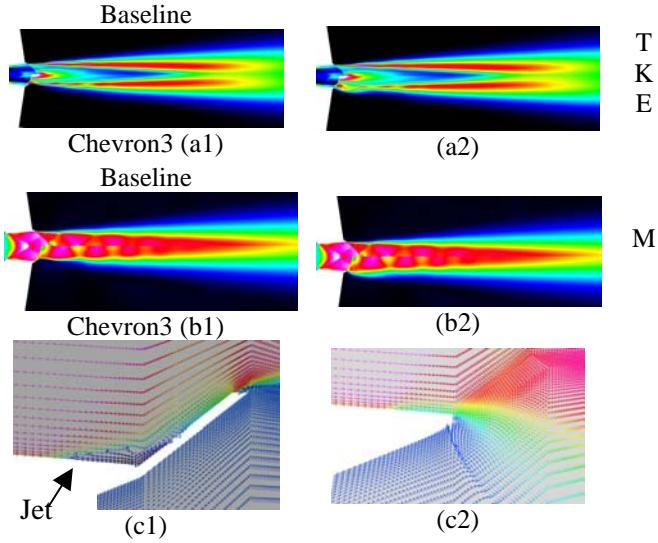
**Fig. 5.** Contours of TKE in xy Plane (Top Half: Standard k- $\epsilon$  Model; Bottom Half: Corrected k- $\epsilon$  Model), (b) Axial Distribution of TKE, and (c) Stagnation Temperature Showing the Effect of Turbulence Model for the Baseline Jet.

Chevron 3 produced the most appreciable change to the flow structure. If the peak TKE levels in the noise producing region are lowered by the use of chevrons, then noise production would be lower. Figure 6 shows the axial distribution of the peak TKE values for the various chevrons studied.

Figures 7 shows the contours of TKE and Mach number for chevron 3, compared with the baseline nozzle and the corresponding velocity vectors in the near vicinity of the chevron. Note the velocity vectors (colored by the streamwise  $u$ -velocity) are plotted with equal magnitude to highlight the re-circulation region. A comparison of the velocity vectors in the near vicinity of the chevrons reveals that chevron 1 and chevron 2 (not shown) disturb the boundary layer from the nozzle walls to a small extent while chevron 3 causes a large re-circulation region that penetrates past the boundary layer and into the core of the jet.



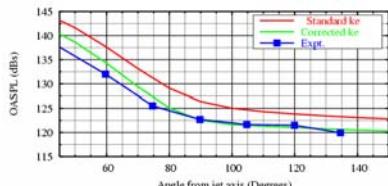
**Fig. 6.** Axial Distribution of Peak TKE Values.



**Fig. 7.** Contours of TKE, Mach number, (compared with baseline) and velocity vectors (top to bottom) in the plane of the chevron (left) and in the symmetry plane between 2 chevrons (right) for the Chevron 3 in 12 configuration.

The location, angle and depth to which a chevron extends into the jet core is quite critical in how effective it can be in altering the flow structure and producing noise suppression. Chevrons 1 and 2 were not effective, while chevron 3 was, as corroborated by NCPA measurements.

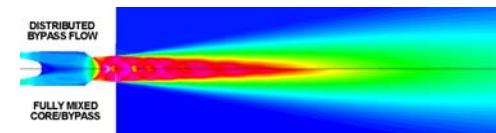
Studying such noise reduction concepts by RANS can reveal how these concepts modify the flow and turbulence structure, but relating these changes to effects on noise suppression is still an active area of research. Preliminary evaluations (using NASA jet noise research code Jet3D [15]) of noise reduction are in progress. Figure 8 shows the OASPL prediction (for observers on an arc of radius equivalent to 55 jet exit diameters from the nozzle exit) by Jet3D for the baseline nozzle compared with that of the NCPA experiment. There is very good agreement with the experimental data for observer angles in the range 50-150 degrees using the corrected  $k-\epsilon$  model – using the standard  $k-\epsilon$  model overpredicts noise levels.



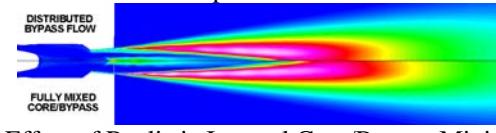
**Fig. 8.** Comparison of OASPL predictions by Jet3D with that of the experiment for the baseline nozzle.

## Real Aircraft/Engine Considerations

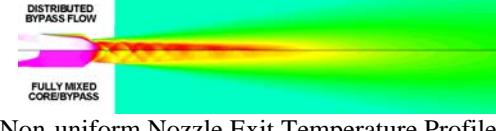
Downstream of the turbine exit station, the internal core/bypass mixing within an actual nozzle consists of a complex series of discrete slot jets and other mixing passages [6]. In contrast, current laboratory simulations assume a single (fully mixed) stream and a simplified augmentor flow path. The impact of this assumption on downstream plume mixing is significant and is illustrated in the following comparative numerical simulations. Two nozzle/plume simulations at the same engine cycle conditions were considered: one representative of the real engine bypass mixing along the engine augmentor and one representing the uniform mixing assumptions of laboratory experiments but at full engine scale. Figure 9(a) compares the resulting Mach number contours of the two simulations and indicates that the “realistic” nozzle yields a shorter jet core length. A significant factor in this result is the large levels of turbulence upstream of the nozzle exit produced by the series of slot jet mixing layers, as shown in Figure 9(b). Additionally, the temperature comparisons of Figure 9(c) show that the exhaust of the “realistic” nozzle is highly non-uniform, with partially mixed bypass flow along the



(a). Effect of realistic internal core/bypass mixing on downstream plume: Mach number



(b). Effect of Realistic Internal Core/Bypass Mixing On Downstream Plume: Turbulent Kinetic Energy

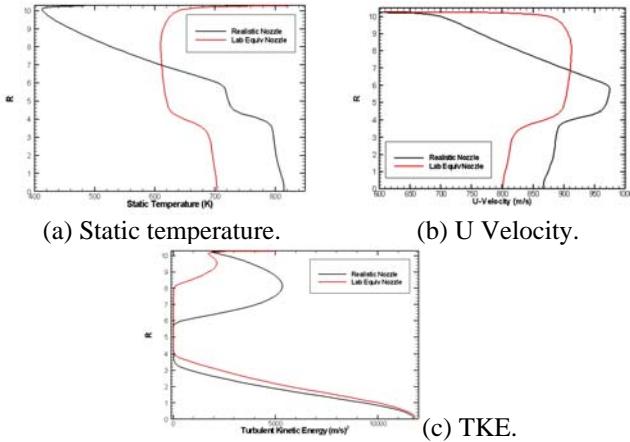


(c). Non-uniform Nozzle Exit Temperature Profile From Upstream Mixing In Realistic F414-400 Augmentor-Nozzle Geometry

**Fig. 9.** Contour Comparisons.

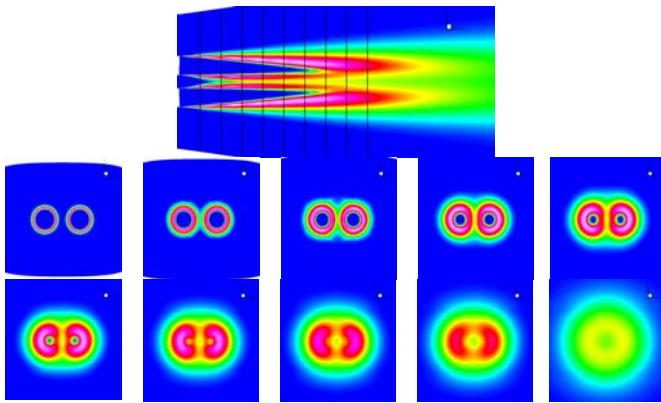
outer nozzle region. Figure 10 shows the radial exit plane distribution of velocity, static temperature and TKE for the realistic nozzle configuration and for the laboratory equivalent nozzle. For the real nozzle one can see the effect of internal bleed/mixing to create a larger boundary layer for both temperature

and velocity with accompanying higher levels of TKE and lower wall temperatures. A chevron designed for the laboratory nozzle will be ineffective for the real configuration because of the differing boundary layers present. CFD is needed to select the ideal location, size and optimal design for maximum effectiveness of these devices in the real engine.



**Fig. 10.** Exit Plane profiles of the nozzle.

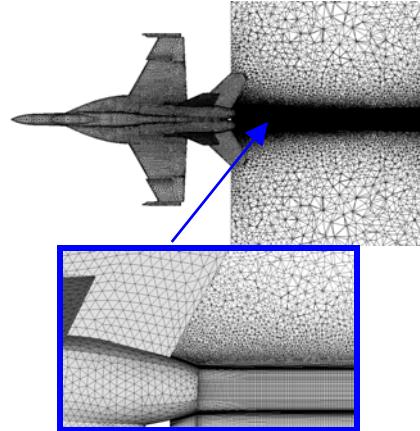
Another area studied was that of plume/plume interactions. On the real aircraft, the nozzles are canted inwards at about  $2^\circ$  towards the vehicle centerline. As shown in Figure 11, for military thrust (MRT) conditions in a static surrounding flow, the plumes coalesce quite early (well before the end of the potential core on each jet). Hence, peak noise will be strongly affected by these interactions. In contrast, for a higher altitude situation at cruise rate thrust (CRT) with a transonic flight velocity, the plumes do not coalesce as quickly (see Refs. 3-5).



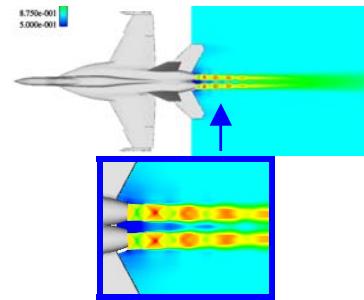
**Fig. 11.** TKE Contours for Dual Plume Interactions for MRT, Static Surrounding Flow.

The last area examined is that of interactions with the vehicle aerodynamics. Figure 12 shows the

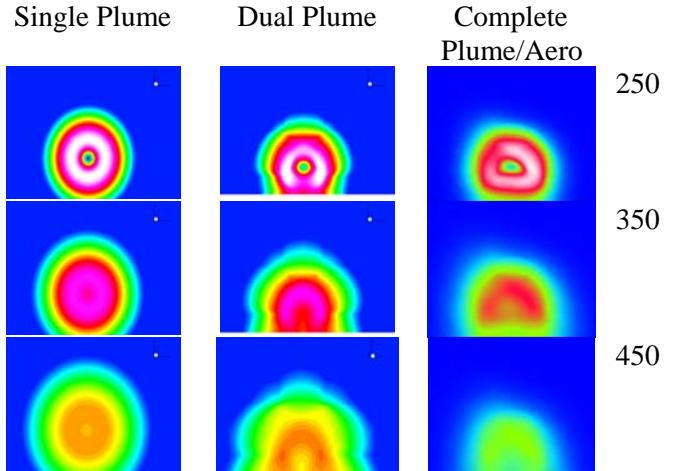
very detailed multi-element unstructured grid required to resolve the plume structure properly. Figures 13 show some details of the plume structure while Figure 14 compares the structure of a single isolated plume, of dual plumes without aerodynamic effects, and of dual plumes with the complete aerodynamic solution, showing the marked differences in structure associated with plume/plume and aerodynamic interactions.



**Fig. 12.** Complete Plume/Aero Calculation.



**Fig. 13.** Complete Plume/Aero Calculation; Over-expanded Jet Due to Elevated Pressure at Tail.



**Fig. 14.** Complete Plume/Aero Calculation; Aerodynamic Effects on Plume.

## Future Plans

Future laboratory jet plans entail using CFD to support the improvement of current concepts as well as studying several new concepts. Use of design optimization techniques will be part of this work. The scale-up and modification of "best"

concepts to support their integration into the engine for ground tests is planned for the very near future, while evaluation of concept performance at flight including plume/plume and aerodynamic effects is an integral part of next years work.

<sup>1</sup> Dash, S.M., Kenzakowski, D.C., and Papp, J., "Progress In Jet Turbulence Modeling For Aero-Acoustic Applications," Paper No. AIAA-2002-2525, 8th AIAA/CEAS Aeroacoustics Meeting, Breckinridge, CO, June 17-19, 2002.

<sup>2</sup> Dash, S.M., Kenzakowski, D.C. Kannepalli, C., Chenoweth, J.D. and Sinha, N., "CFD Simulations Of Supersonic Jet Noise Reduction Concepts," Proceedings of the Fifteenth ONR Propulsion Meeting, Washington, DC, pp. 136-142, August 5 to 7, 2002.

<sup>3</sup> Dash, S.M., Kenzakowski, D.C., Kannepalli, C., and Chenoweth, J.D., "CFD Simulations of Supersonic Jet Noise Reduction Concepts for Application to F/A-18 E/F Aircraft," ONR Midyear Combustion Control and Noise Reduction Review, University of Southern California, Los Angeles, CA, January 16-17, 2003.

<sup>4</sup> Kannepalli, C., Kenzakowski, D.C., and Dash, S.M., "Analysis Of Supersonic Jet Noise Reduction Concepts," Paper No. AIAA-2003-1201, 41<sup>st</sup> AIAA Aerospace Conference & Exhibit, Reno, NV, Jan. 6-9, 2003.

<sup>5</sup> Kannepalli, C., Kenzakowski, D. C. and Dash, S.M., "Evaluation Of Some Recent Jet Noise Reduction Concepts," Paper No. AIAA-2003-3313, 9th AIAA/CEAS Aeroacoustics Conference & Exhibit, May 2003, Hilton Head, SC.

<sup>6</sup>Cavallo, P.A., Kenzakowski, D.C., and Dash, S.M., "Axisymmetric Flowfield Analysis of the F414-400 Turbofan and Exhaust Plumes," Technical Final Report, Report No. CRAFTR-10/97.014, October 1997.

<sup>7</sup> Seiner, J.M., Jansen, B.J., Ukeiley, L, Ponton, M.K., " Acoustic Fly-Over Studies of F/A-18 E/F Aircraft During FCLP Mission," ONR BAA 01-016, Jet Noise Suppression Technologies for Military Aircraft, Task 1: Final Report, NCPA, U. MISS, December 2002.

<sup>8</sup>Papp, J.L. and Dash, S.M., "Turbulence Model Unification and Assessment for High-speed Aero-propulsive Flows", AIAA-2001-0880, 39th AIAA, Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan 2001.

<sup>9</sup>Chidambaram N., Dash, S.M., and Kenzakowski, D.C., "Scalar Variance Transport in the Turbulence Modeling of Propulsive Jets," *Journal of Propulsion & Power*, Jan - Feb., 2001.

<sup>10</sup>Kenzakowski, D.C., Papp, J., and Dash, S.M., "Evaluation of Advanced Turbulence Models and Variable Prandtl/Schmidt Number Methodology for Propulsive Flows," AIAA Paper No. 2000-0885, 38<sup>th</sup> AIAA Aerospace Sciences Meeting at Reno, NV, Jan. 10-13, 2000.

<sup>11</sup>Papp, J.L., Kenzakowski, D.C., and Dash, S.M., "Calibration and Validation of EASM Turbulence Model for Jet Flowfields," Paper No. AIAA-2002-0855, 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 14-17, 2002.

<sup>12</sup>Kenzakowski, D.C., Papp, J.L., and Dash, S.M., "Modeling Turbulence Anisotropy For Jet Noise Prediction," Paper No. AIAA-2002-0076, 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 14-17, 2002.

<sup>13</sup>Seiner, J.M., Ponton, M.K., Jansen, B., and Lagen, N.T., "The effects of Temperature on Supersonic Jet Noise Emission," DGLR/AIAA 14<sup>th</sup> Aeroacoustics Conference, Aachen GE, May 1992.

<sup>14</sup>Calhoon, W. H. Jr., Arunajatesan, S., and Dash, S.M., "Heat Release And Compressibility Effects On Planar Shear Layer Development," Paper No. AIAA-2003-1273, 41<sup>st</sup> AIAA Aerospace Conference & Exhibit, Reno, NV, Jan. 6-9, 2003.

<sup>15</sup>Hunter, C.A., and Thomas, R.H., "Development of a Jet Noise Prediction Method for Installed Jet Configurations," 9<sup>th</sup> AIAA/CEAS Conference and exhibit, 12-14 May 2003/ Hilton Head, SC.